Estimation of Grapevine Crop Mass and Yield via Automated Measurements of Trellis Tension

J. M. Tarara, J. C. Ferguson, P. E. Blom, M. J. Pitts, F. J. Pierce

Abstract. *A novel approach was devised to estimate vegetative growth and fruit mass (i.e., yield) in grapevines by continuously measuring the tension in the horizontal (cordon) support wire of the trellis. Load cells installed in−line with the cordon wire were connected to an automated data acquisition system, a major departure from the viticulture industry's standard method of collecting fruit samples by hand two or three times per growing season. Each experimental row in the vineyard was calibrated to determine the change in tension in that row in response to an increase in known mass on the cordon wire. The effects of temperature on wire tension were removed by post−processing with a regression−based empirical protocol, which corrected the raw data to a standard temperature. Because data were averaged over 15 min, wind gusts appeared to have little measurable effect on the tension measurement. A smoothing algorithm removed remaining transient disturbances in the data without masking significant events like crop thinning or harvest. Results to date suggest a linear relationship between wire tension and fruit mass that varies among rows, but not within a row, during a single season. Yields were between 4.5 and 20.2 t ha^{-1} (2 to 9 t acre^{-1}).*

Keywords. *Crop estimation, Grapes, Load cell, Vitis, Yield estimation.*

Worldwide, grapes are the most planted fruit crop (7.4 million ha; FAOSTAT, 2003) and rank third in tonnage produced (62.4 Mt; FAOSTAT, 2003). Grapes destined for juice or wine are relatively high in value and perishable; processing generally is desired within hours of harvest. Because processing infrastructure is finite and costly to expand, juice processors and wineries want to predict yield accurately and as far in advance as possible to schedule harvesting, processing, fermentation, and storage. Furthermore, because maximum quality in grapes occurs at something less than maximum potential yield, growers of premium fruit desire yield estimates early in the growing season to thin excessive crops. The current method of estimating yield in grapevines (summarized below) is labor−intensive, producing both limited data and a static prediction. The standard technique has been documented in trade publications (e.g., Haeseler, 1987; Spayd and Wample, 1995) but has not been systematically reported in the peer−reviewed scientific literature. Large vineyards, wineries, and juice processors consistently apply this method, although some details of what is described below vary in practice.

Yield estimation is a multi−step process. Before bloom, the average number of clusters per vine is determined on either indicator vines sampled annually or on randomly selected vines in a vineyard block. After fruit set, the average number of berries per cluster is determined on the same vines. Once or twice per season thereafter, either whole−cluster or berry samples are collected and used to calculate the average weight per cluster or berry. These values are compared with those from previous years considered to be biologically and meteorologically similar to the current growing season. Final berry or cluster weight (i.e., yield) is projected using a ratio of the current sample weight to a comparison year's sample weight for the same sampling date (Price and Lombard, 1988). Self−reporting suggests that the industry−wide accuracy of estimating final yield is ±10% (N. Dokoozlian, personal communication, 22 March 2002), with larger, older operations achieving the best results due to adequate staffing and corresponding extensive historical databases of cluster weights and yields.

However, due to its limited sampling frequency, this standard estimation method fails to provide an indication of the dynamics of berry growth, which change with variety and season at a given site. While there are guidelines for establishing adequate sample sizes (Wolpert and Vilas, 1992), the cost and time involved in hand sampling impose practical limits on the spatial and temporal coverage of the dataset. An automated method of yield estimation would not only save time and labor but would also provide continuous data during fruit development, information that could result in an increase in the efficiency and precision of vineyard management. Loads on posts in orchards have been measured for the purpose of designing sufficiently robust trellises (Young, 1983; Young and Jerie, 1985), but measurements of wire tension in trellises have not been utilized for estimating crop yield. In the research reported here, a novel method of estimating yield in grapes was developed by using automated measurements of the within−season changes in tension in the horizontal support wire of the trellis (described below) upon which the grape−

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The authors are **Julie M. Tarara,** Research Horticulturist, **John C. Ferguson,** Electronics Technician, and **Paul E. Blom,** Research Biologist, USDA−ARS Horticultural Crops Research Unit, Prosser, Washington; and **Marvin J. Pitts, ASAE Member Engineer,** Associate Professor, Department of Biosystems Engineering, and **Francis J. Pierce,** Director, Center for Precision Agricultural Systems, Washington State University, Pullman, Washington. **Corresponding author:** Dr. Julie Tarara, USDA−ARS Horticultural Crops Research Unit, 24106 N. Bunn Road, Prosser, WA 99350−8694; phone: 509−786−9392; fax: 509−786−9277; e−mail: jtarara@wsu.edu.

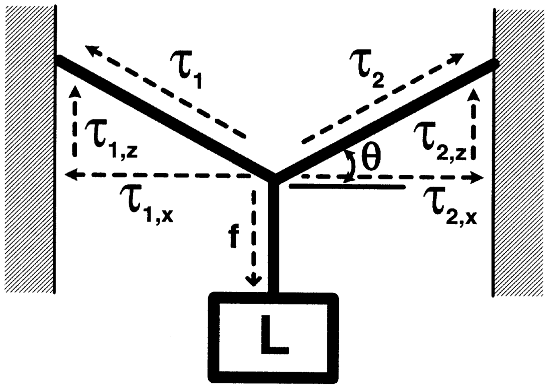

Figure 1. Free body diagram of an idealized trellis system where the vine is a load (L) hanging from a wire that is strung between two fixed end posts. The tension (τ) in the wire is resolved into horizontal (*x*) and vertical (*z*) components. The angle (θ) between the wire and the horizontal is a primary determinant of the sensitivity of the system to a change in load, resulting in the tensile force (*f*) applied by the load.

vines are trained. Load cells were used to measure the wire tension.

Theory

Grapevines in their native environment grow prolifically but are not freestanding like trees and shrubs; rather, vines use trees as supports for their semi−rigid trunks, growing to the top of the tree canopy to expose their fruit clusters to sunlight. Domestic grapevines are highly manipulated to reduce vegetative growth, increase fruit production, and maintain the vine in a form that is amenable to agricultural management (i.e., in rows and under 2 m tall). Grape growers provide a support structure for the semi−rigid vine trunk with a trellis, the designs of which vary but share the common features of evenly spaced support posts and at least one horizontal support wire strung from post to post.

In simplified form, a trellised grapevine can be considered a concentrated load (L) hanging on a wire strung between two fixed end posts (fig. 1). The vertical component of the tension (τ_z) is equal on either side of the load ($\tau_{1,z} = \tau_{2,z}$), is a function of the total force (*f*) due to the load:

$$\tau_z = \frac{f}{2} \tag{1}$$

and is a function of the angle (θ) between the wire and the horizontal:

$$\tau_z = \tau \sin\theta \tag{2}$$

where τ is the total tensile force on the wire. By substitution:

$$\tau = \frac{f}{2\sin\theta} \tag{3}$$

As θ decreases, τ increases, suggesting that in practice a higher initial tension in the wire results in greater responsiveness, i.e., a larger change in τ per unit change in *f*. Thermal expansion or contraction of the wire affects θ and thus τ. Likewise, any change in the length of the wire due to strain will change the geometry of the system, affecting θ. Wind applies a transient force to the wire.

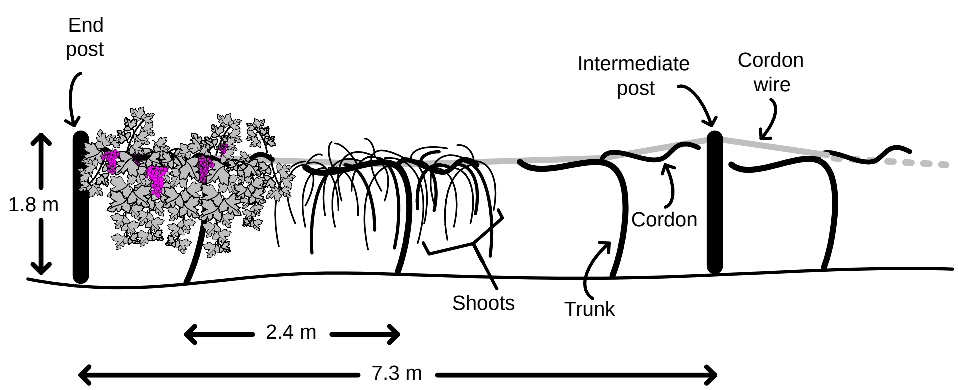

Figure 2. Schematic diagram of a vineyard row.

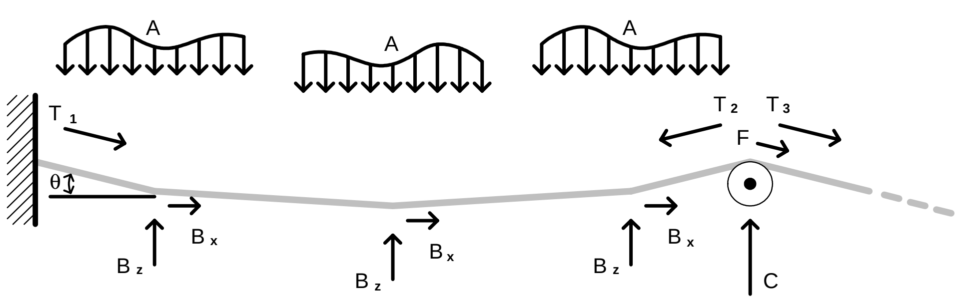

Figure 3. Force diagram of a vineyard row. Trunks apply both vertical (B_z) and horizontal (B_x) forces to the wire. T_1 = wire tension at fixed end post; T_2 and T_3 = wire tension on each side of intermediate post; F = friction force of pulley acting on wire at intermediate post (magnitude of F = $T_2 - T_3$); A = unevenly distributed load from plant mass (fruit, leaves, shoots) and wire mass; C = vertical support at intermediate post; and θ = wire angle from horizontal, which varies from point to point (±10°).

Figure 4. Trellis structures: (a) load cell in line with cordon wire, near the end post, (b) cordon growth around the cordon wire, and (c) pulley to support the cordon wire at an intermediate post.

The loads and support structures in a commercial vineyard are much more complex. A vineyard row includes any number of trunks with varying diameters, spaced approximately equally between intermediate posts (fig. 2). In any given trellised row, the load is unevenly distributed and consists of the mass of trunk, cordon (horizontal extension of the trunk), shoots, leaves, fruit, and the wire itself (fig. 3). Both ends of the row are fixed by wood or steel posts that are usually, but not always, secured by an anchor. Along the row, θ varies from vine to vine and from post to post because the curvature of the trunk and the height of individual cordons, thus the height of the cordon wire, can vary from vine to vine. Trunk diameters and their rigidity change seasonally and in response to irrigation. Ideally, tension in the cordon wire would be transmitted entirely to the end post, offering maximum sensitivity for a measurement of tension at that location (fig. 4a). In practice, a number of trellis and vine structures partially support the load, directly reducing the amount of load supported by the cordon wire. Vertical support structures are the intermediate posts and the vine trunks. Cordons that grow around the wire (fig. 4b) and clips that hold the wire snugly against the intermediate post, which most vineyards use, induce horizontal forces on the wire. Ideal pulleys could allow tension to be transmitted equally to either side of the post; however, real pulleys (fig. 4c) are not frictionless. In addition, the current season's growth, like tendrils and canes, may also bind the wire. Finally, the change in tension between fruit set and harvest is due to total crop mass, defined as the sum of vegetative (shoots and leaves) and reproductive (fruit) masses. However, yield refers only to fruit mass, the harvested portion of the crop.

OBJECTIVES

Theory suggests a direct relationship between tension in the trellis wire and fruit mass, but actual vine and trellis components complicate that relationship. Our objectives were to pursue an empirical approach that would quantify the relationship between tension in the cordon wire of a grapevine trellis and the fruit mass by: (1) identifying the influences of temperature and wind speed on wire tension, (2) determining whether the relationship between tension and total crop mass changes during the growing season, (3) estimating the sensitivity of the load cell to crop mass as a function of the distance between the load and the load cell, and (4) determining if the contribution to wire tension due to fruit mass can be extracted from the total tension due to crop mass, i.e., the sum of fruit and vegetative masses.

MATERIALS AND METHODS

A 0.34 ha vineyard (*Vitis labrusca* L. cv. Concord) near Prosser, Washington (46.30° N, 119.75° W) was used for the experiment. Of the 11 vineyard rows, 9 were used for experimental treatments with the outermost rows left as buffers. Planted in 1981, the vines had been grown with a single trunk trained to a bilateral cordon at about a 1.7 m height and were spur−pruned annually. There were 2.4 m between vines and 3.0 m between rows, which were oriented north−south. The trellis consisted of wood posts (12 cm dia., 3.0 m long, 1.7 m above ground) at 7.3 m intervals along the row. A single wire (3.66 mm dia.; 9 SWG [Standard Wire Gauge], galvanized) strung from post to post at cordon height supported the vines (fig. 2). Some of the cordons had grown around the wire.

The trellis was retrofitted to maximize the transfer of tension along the cordon wire to a load cell near the end post. Wood end posts, which can shift in soil, were replaced with 3.2 m long steel pipe (11.4 cm o.d., 10.8 cm i.d.). The pipe was placed in a 0.9 m deep, 0.3 m diameter post−hole and then driven about 0.6 m into the undisturbed soil below. Concrete was used to fill the hole. A short cantilever was welded atop the post, and an aluminum benchmark plate was cemented to the ground directly below so that any shift in the post's position could be detected with a plumb line. Staples that stabilized the cordon wire atop intermediate posts were removed and replaced with pulleys free to rotate at about 1.7 m on the side of the post (fig. 4c). Existing splices in the cordon wire were clamped and painted to provide a visual indicator of slipping.

A load cell (RSC−3K−25100, HBM, Inc., Marlboro, Mass.) was placed in−line with the cordon wire between the wire end and an eyebolt about 10 cm below the top of the end post (fig. 4a). The eyebolt was used to fine tune initial tension, which was set manually soon after bud break (day of year [DOY] 117). Because the tension was not uniformly transmitted from one end of the row to the other, the initial tension at the north end of all rows was set to about 1,000 N and at the south end to about 500 N. Unequal tension was partly due to the introduction of static force on the wire by the growth of some cordons around it (fig. 4b) and by friction in the pulleys (fig. 4c) at the intermediate posts.

The load cells' linear output voltage was scaled and offset to produce a calibrated output for a 0 to 1800 N range of force. The five−point calibration was done using a total of 180 kg of dead weight. Previous work in this vineyard suggested that the tension on the cordon wire typically would not exceed 1500 N (Keenan and Ferguson, unpublished data). The temperature of the cordon wire was measured with three thermocouples wired in parallel (Type T) and glued to the underside of the wire at each end of the center row. Signals from the load cells and thermocouples were scanned every 5 s and averaged every 15 min by a datalogger and multiplexer (CR−10X and AM416, Campbell Scientific, Logan, Utah). Measurements were recorded between DOY 120 and DOY 305 (leaf fall). Wind speed at a height of 2 m was measured by 3−cup anemometer (Wind Sentry, R.M. Young Co., Traverse City, Mich.) at the Public Agriculture Weather System station located about 700 m from the vineyard.

One of three levels of fruit load, or potential yield, was imposed over an entire row in a randomized complete block design with blocks consisting of three rows of equal length (85, 95, or 107 m). On DOY 182, vines had either all fruit removed (no crop [NC]), alternate clusters removed (half crop [HC]), or no clusters removed (full crop [FC]). At thinning, berries were just beyond "pea size," a recognized viticultural stage (Eichhorn and Lorenz, 1977, as modified by Coombe, 1995) that is defined by the average size of the berries on the cluster. The NC rows served as indicators of the fraction of wire tension due to vegetation.

The fresh mass of reproductive (fruit) and annual vegetative tissues (green shoots and leaves), or total crop mass, was estimated five times during the growing season that corresponded to the grape industry's sampling dates or to key phenological stages. Shoots, leaves, and fruit were stripped from one vine per row, separated, and immediately weighed to the nearest 0.1 g. Vines were selected from the middle of each row to minimize the effect of removing mass on the tension at the load cell. The small size of the vineyard and the perennial nature of the crop precluded more extensive destructive sampling.

On the same days that total crop mass was estimated by destructive sampling, known mass was hung from the cordons to evaluate the system's response to loading and to indicate any shift in the sensitivity of the system over time. Three 3.8 kg weights were hung incrementally at each vine to simulate yields of 1.5 to 4.6 kg m^{-1} of row (5 to 15 T ha^{-1}). Each vine in a row received one weight before the next was hung. The system was allowed to equilibrate for 5 min between each weight set.

From DOY 182 until harvest, irrigation was controlled to maintain soil water in the root zone between 10% and 15% by volume to minimize shoot growth during the period of fruit growth (deficit irrigation). Fruit was picked by hand in three partial harvests on DOY 261, 264, and 267, removing all fruit from every third vine on each day. Fruit mass per vine, average mass per cluster, and average mass per berry were recorded.

A correction for thermal expansion was developed empirically. Wire tension was regressed on wire temperature (°C) for the 48 h preceding each of the five dates on which known mass had been hung from the trellis and at harvest, when the final fruit mass was measured. This was done for each row end under the assumption that there was negligible increase in fruit mass during that 48 h period. Each trellised row and row end would be expected to have its own temperature coefficient because of inherent variability in the wires, vines, and attachment points. Slopes from the sample dates were compared within each row end using a test for heterogeneity of slope (Littell et al., 1991). Using the slopes from these regression equations, raw tension data within each end row (n = 192) were corrected to a standard temperature of 20°C using equation 4:

$$\text{Tension}_{\text{corrected}} = (\text{Tension}_{\text{uncorrected}}) + [(20^{\circ}\text{C} - \text{Temperature}_{\text{wire, current}})(\text{slope})] \quad (4)$$

A 48 h moving average was applied to the temperature−corrected data, with a minimum of 96 observations required for an estimate to be made.

Results and Discussion

Correction for Wire Temperature

As expected, temperature affected tension in the cordon wire. Early in the season, while the wire is fully exposed to solar radiation, heating and cooling patterns differed, suggesting that the wire did not stretch or contract uniformly (fig. 5a). It is possible that the cordon wire contracts in "bursts" that correspond to the dynamic tension (i.e., contracting by cooling) overcoming static forces that are imposed by attachment points like pulley friction and the growth of cordons around the wires. It may be possible to use air temperature, a variable easier to measure than wire temperature, as a surrogate for wire temperature. However, to do this, one would have to account for the influence of the foliage shading the wire, which varies during the season. By midseason, when the canopy fully shaded the wire, diurnal hysteresis was much less perceptible (fig. 5b). While this hysteresis might be a concern for short−term estimations (within 24 h), it is insignificant within the context of seasonal yield prediction and the use of 48 h smoothing for the temperature−corrected estimates of tension.

At both ends of the vineyard, the magnitude of wire tension varied tremendously during the season, as is evident in the intercept values of the tension−temperature relationships at different phenological stages and amounts of fruit mass on the vines (fig. 6; $P > F < 0.0001$, d.f. = 4). In some FC rows, wire tension approximately doubled between bloom and harvest, a large enough response to support the proposal that estimates

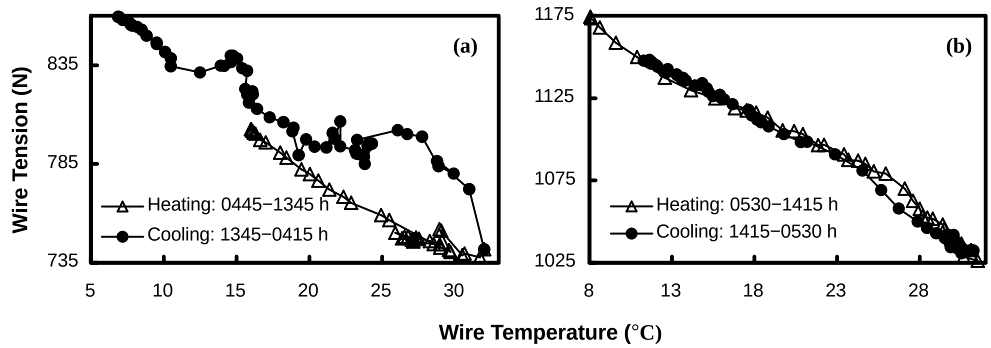

Figure 5. Relationship between wire tension and wire temperature over a diurnal heating−cooling cycle: (a) pronounced hysteresis that can occur early in the season before extensive canopy development, and (b) full canopy about 85 days post bloom.

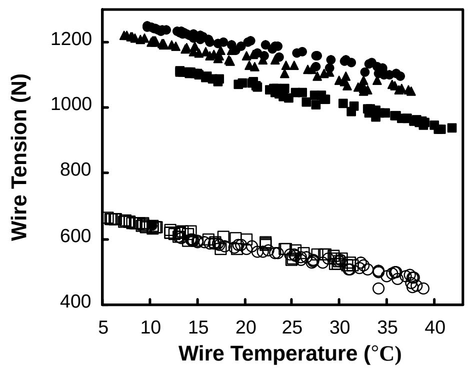

Figure 6. The relationship between wire tension and wire temperature for one row end from five 48 h periods during the season: white circles = DOY 143, pre−bloom; black squares = DOY 189, pea−sized berries; black triangles = DOY 237 (85 days post−bloom), veraison; black circles = DOY 254, pre−harvest; white squares = DOY 274, post−harvest. The range of tensions experienced by the trellis wire varied greatly through the season, as is evident in the different intercepts. However, the slopes, necessary for temperature correction, remained similar throughout the season.

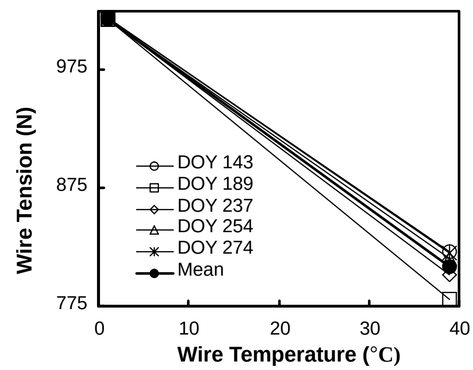

Figure 7. Predicted relationship between wire tension and wire temperature for one row with intercepts normalized to an average tension of the five regression−derived parameters for direct comparison of slopes.

of fruit mass might be made from automated measurements of wire tension. For any given row, the slopes of the tension−temperature relationship estimated at different dates were significantly different in a test for heterogeneity of slope (fig. 6; P > F < 0.0001, d.f. = 4). However, these differences between slopes were small (fig. 7), and the expected tensions computed from date−specific slopes differed on average by only 1.2% (range 0% to 5.6%) from the tensions computed using the average of five slopes from across the season. Thus, the averaged slope for each load cell installation was used to correct tension for diurnal temperature effects.

Smoothing Temperature−Corrected Tensions

Correction for the effects of diurnal temperature cycling (eq. 4) removed much of the short−term noise in the 15 min averages of the wire tension measurements (figs. 8a and 8b). The seasonal trend in wire tension can be smoothed further by estimating each 15 min average value with a moving 48 h window, using neighborhood values 24 h to either side of the point (fig. 8c). At all steps of data processing, major events remain evident with the accumulation or loss of tension in the trellis wire. For example, between DOY 148 and approximately DOY 185, a rapid increase in shoot length and crop mass is apparent. At DOY 181, the NC and HC treatments were applied, and these are easily seen by corresponding proportional drops in wire tension. Although final smoothing of the data could obscure short−term events, small plateaus marking harvest (DOY 261, 264, 267; approximately 3 h duration each day) persist in the tension curves (fig. 8c).

Effects of Wind

Wind visibly moves trellis wires, thereby affecting trellis tension. Wind in this experiment might be categorized two ways: (1) typical, short−duration breezes of 1 to 2 m s^{-1} (fig. 9a), and (2) stronger winds gusting over 5 m s^{-1} and lasting several hours or longer (fig. 9d). In the former, there was no apparent relationship between wind speed and wire tension (fig. 9b). For these minor breezes it is probable that 15 min integration of 5 s measurements from the load cell removed the effects of wind on the signal. More sustained winds had a measurable effect on wire tension (fig. 9e). However, because the intention of measuring tension in the trellis wire is to follow season−long patterns, the influence of these more sustained winds can also be minimized by the 48 h smoothing routine. Pronounced increases in tension due to sustained high winds appear as a “bump” in the smoothed tension data (fig. 9f). The user could compensate for this effect. To minimize wind−related errors on both scales, high−frequency tension measurements should be averaged for at least several minutes (e.g., 10 to 15 min) and the final data set smoothed with a sufficiently large moving average (e.g., 100 time−averaged data points).

Response of Temperature−Adjusted Tension to Known Mass

The response of the system to additions of known mass was linear, although a 1:1 relationship between mass and tension

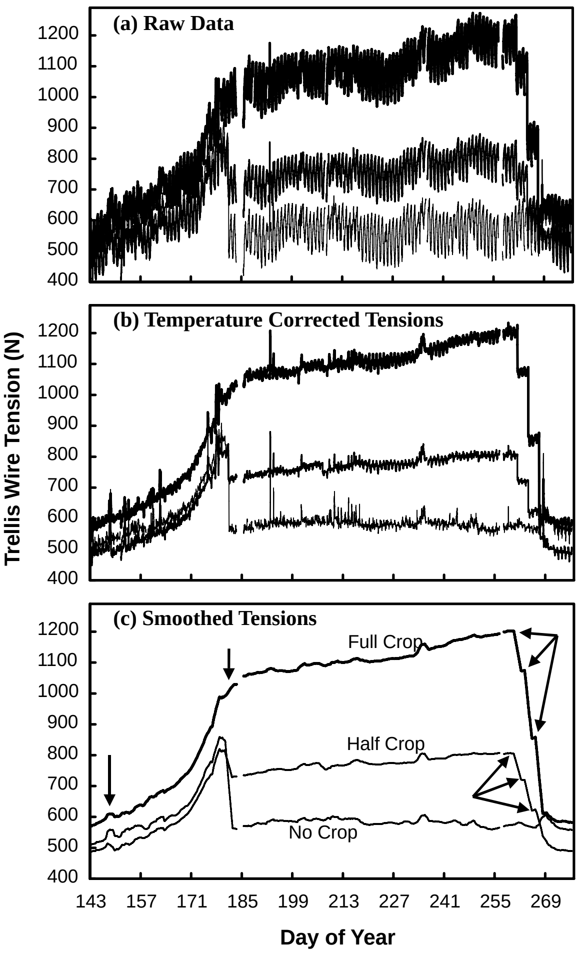

Figure 8. Tension in the cordon wire from DOY 143 to 276 for (top to bottom in each panel) full−cropped vines, vines from which one half of all clusters had been removed (half crop), and vines from which all fruit had been removed (no crop). The raw tension values (a) have been corrected for effects of diurnal temperature cycling in (b). Other short−term oscillations are smoothed (c) by 48 h averaging with a floating window centered on the estimated value. Arrows indicate bloom (DOY 148), the date of cluster thinning (DOY 181), and the three harvest dates (DOY 261, 264, 267).

was not expected because the mass was partially supported by posts and trunks. As might be expected because of structural variations between vineyard rows (e.g., posts, vine attachment to the trellis wire), on some dates during the season there were significant differences between rows in the linear relationship between the cumulative increase in wire tension and the cumulative increase in known mass (table 1, fig. 10). In a commercial vineyard, one should anticipate independently calibrating each row that is equipped with a load cell. The load cells in this experiment apparently provided a real−time record of fruit and vegetative mass because a row's response to known mass did not shift during the season. Within a row end, on only two occasions were there potentially significant differences between slopes (table 2, fig. 11). On these two dates, statistical significance should be interpreted cautiously because of the small number of observations. Data within each row end were pooled across the season, and a single linear relationship was developed between accumulated mass and accumulated wire tension for each row end. In practice, calibration with known mass on a single date should suffice to predict the mass−tension relationship for the entire growing season, with one caveat: for a measurement near an end post, one must be certain that the post does not shift during the season, which would change the geometry and baseline tension of the system, and thus the relationship between the change in tension and crop mass. In this vineyard, when data were pooled over all rows, slopes were similar for north and south ends of the trellis (fig. 12). Differences in the two intercepts reflect the differences in initial wire tensions.

The row ends that had been set with higher initial tension (about 1,000 N, north) had greater sensitivity (21.2%) to an increase in mass (fig. 12) than those set at a lower initial tension (about 500 N, south), as would be expected from equation 3. In a commercial vineyard, it would simplify the system to set a uniform initial tension in all sample rows, selecting that tension to optimize sensitivity. After harvest, wire tension returned to nearly the value recorded before fruit set in FC and HC rows, and to that recorded after the removal of all clusters in the NC rows (fig. 8). This return to initial values suggests that the system did not store energy and that there was little detectable growth in vegetation after DOY 182.

Effect of Distance from Load Cell

To some extent, the trellis structure and the vines attenuate the transfer of added tension to the load cell. With known mass added to the cordon in 3.8 kg increments at every vine, we observed a decline in sensitivity with distance from the load cell. This relationship was modeled as an exponential decay (fig. 13) and varied substantially from row to row. Taking the intersection of the lower 95% confidence limit for each row as a measure of the effective distance, on average an increase in mass was undetected at approximately 55 m from the load cell (n = 18, SE = 4.7, range 26.2 to 82.9 m). Consistent with the difference in sensitivity between the row ends, a change in mass was detectable at a greater distance from the load cell at the north end (mean = 69.8 m, n = 9, SE = 4.6, range 43.3 to 82.9 m) than from the load cell at the south end (mean = 39.8 m, n = 9, SE = 3.9, range 26.2 to 59.1 m). In practical terms, a tension measurement will be dominated by the fruit hanging nearest the load cell. The end post may not be the best location for a load cell if one wishes to maximize the length of the sampling unit per instrument. Placing the load cell in the middle of a row might increase the length of the sampling unit by allowing tension to be detected on both sides of the sensor. In addition, vines at the ends of rows likely represent an "edge effect" and may not correspond to the mean overall yield of an individual row or of the vineyard. In vineyards where cordon wires are firmly stapled or clipped to intermediate posts, one might expect the sensitivity of the measurement to decline more rapidly away from the load cell than in this experiment where all staples were replaced with low−friction connectors. Vineyards in which cordons have not grown around the wire could improve the transmission of tension along the wire.

Not all tension in a cordon wire is transmitted directly to the end post for several reasons: (1) the pulleys on intermediate posts do not transmit tension equally to either side of the pulley, (2) curved trunks pull the wire horizontally, and (3) cordons that have grown around the wire limit lateral transmission of tensile force. In new vineyards, the sensitivity of a wire tension measurement could be increased by suspending cordons from the wire rather than wrapping them around the wire. It may be easier to estimate yields from wire tension under "cane pruning," a practice that renews annually the horizontal vine structure, because the cane (two−year−old

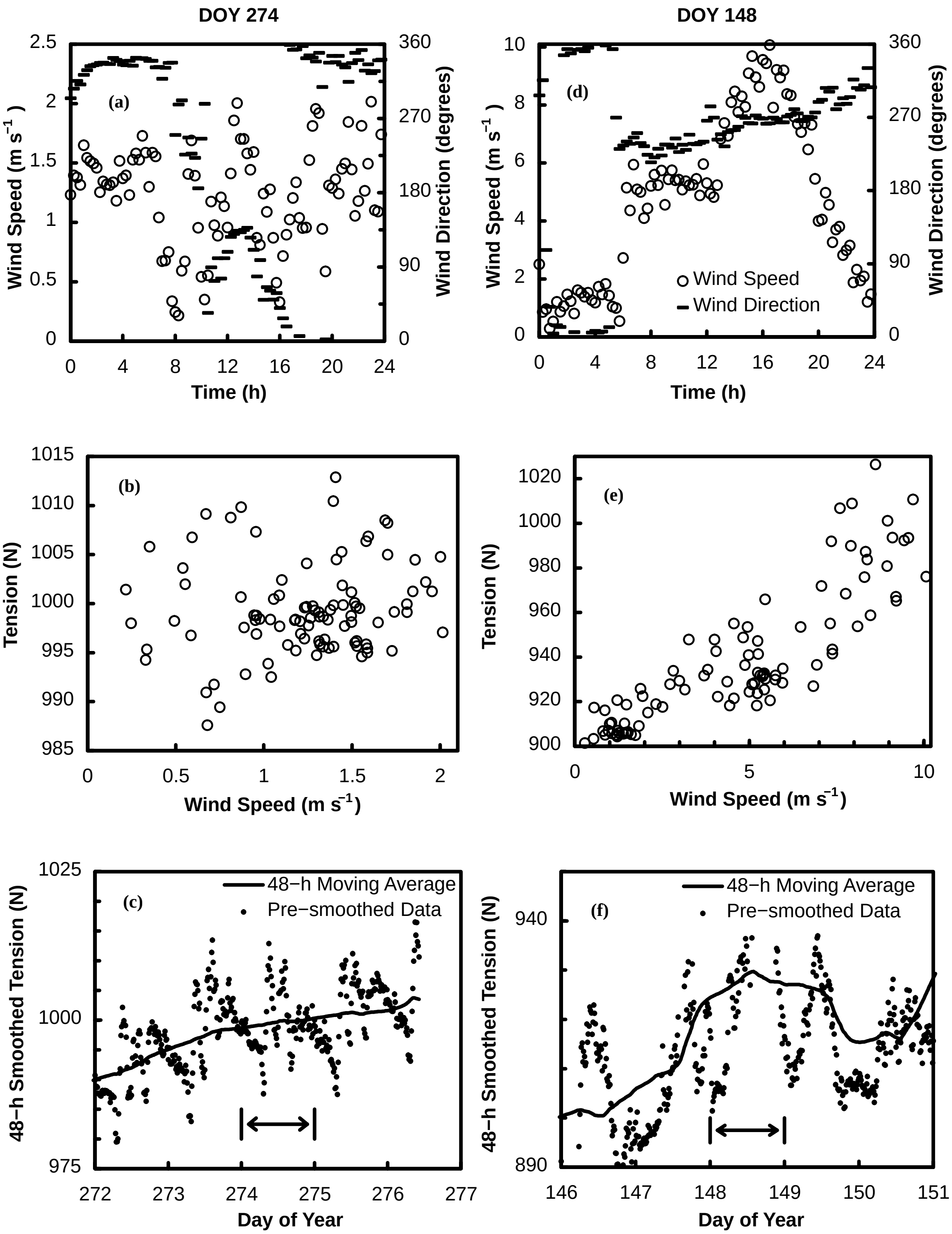

Figure 9. Effects of wind on trellis wire tension. Panels (a) through (c) illustrate DOY 274, a characteristic day with light breezes of short duration, while (d) through (f) show the most extreme winds experienced in 2001 (DOY 148). DOY 148 had sustained winds of about 5 m s^{-1} for several hours in the mid−morning, climbing to a peak of about 10 m s^{-1} by late afternoon. A westerly wind direction was fairly constant during this period. Tension increased with wind speed on DOY 148 (e). This response of approximately 120 N was reduced to a swell in the tension of about 20 N when the data were processed with a smoothing algorithm to remove diurnal hysteresis (f). Smoothing spread the wind effects into tension estimates of the surrounding days. The 24 h centered on the wind disturbances are identified by double−headed arrows in (c) and (f).

wood), which is suspended from the horizontal trellis wire, bears less of the load than would a large cordon. The extent to which the trunk stores potential energy varies during the season as the trunk hydrates with irrigation (van Leeuwen et al., 2000) and as it responds to increasing crop load. Some trellis systems, like Geneva Double Curtain, train the trunk at cordon height to a right angle perpendicular to the row. In this system, the vegetation and fruit hang like a curtain in a separate vertical plane parallel to that of the trunks and intermediate posts; tension may be transferred more effectively to a load cell at the end of a curtain wire than at the end of a single−wire trellis.

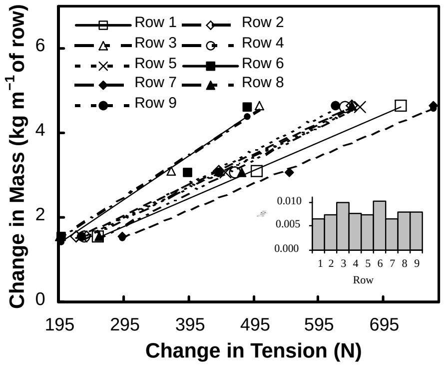

Figure 10. Accumulated change in mass as a function of accumulated change in tension of the trellis wire measured at the north end of all experimental rows. Lines were predicted by linear regression using data collected on DOY 256 from known mass (*n* = 3) hung on the cordons. Differences among slopes were significant on this date (see table 1).

Table 1. General linear model for the interaction between cumulative change in tension (N) with known mass and row within the north or south end of the vineyard and day of year. A significant interaction indicates the presence of different slopes.

Row End	DOY	d.f.	SS	F	Pr > F
North	139	7	0.18836	1.5197	0.28428
	187	8	0.55175	16.8222	0.00015[a]
	208	7	0.60306	1.9787	0.17963
	236	8	1.23552	6.7488	0.00486[a]
	256	8	0.87836	3.2238	0.05025[b]
South	139	7	0.82190	16.0426	0.00040[a]
	187	8	0.88938	2.1111	0.14336
	208	8	1.24829	1.2763	0.35986
	236	8	1.31278	1.6607	0.23261
	256	8	1.89487	3.2158	0.05059[b]

[a] Considered significant.
[b] Significance questionable in the context of small number of observations.

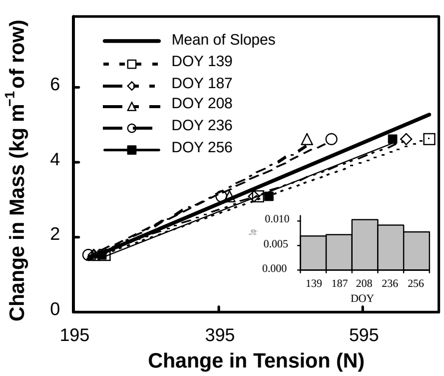

Figure 11. Accumulated change in mass as a function of accumulated change in tension of the trellis wire at the north end of row 4. These predicted fits are from observations in each DOY, using known mass (*n* = 3) (see table 2).

Table 2. General linear model for the interaction between cumulative change in tension (N) with known mass and DOY within the north or south end of each row of the vineyard. A significant interaction indicates the presence of different slopes by date.

Row End	Row	d.f.	SS	F	Pr > F
North	1	4	0.03958	1.81431	0.26359
	2	3	0.14869	8.07512	0.03583[a]
	3	4	0.21638	2.98358	0.13083
	4	4	0.48394	3.61005	0.09585
	5	4	0.51578	9.17745	0.01592[a]
	6	4	0.74883	2.09397	0.21917
	7	4	0.19332	3.80943	0.08745
	8	4	0.21289	2.44498	0.17668
	9	3	0.07061	2.36861	0.21171
South	1	4	0.33565	2.80650	0.14388
	2	4	0.05529	0.14387	0.95811
	3	4	0.46313	1.36938	0.36293
	4	4	0.14915	2.83901	0.14135
	5	4	0.22371	0.79487	0.57606
	6	4	0.40112	0.59297	0.68360
	7	4	0.17975	1.69282	0.28669
	8	4	0.25595	3.02230	0.12820
	9	3	0.18035	0.38123	0.77285

[a] Significance questionable in the context of small number of observations.

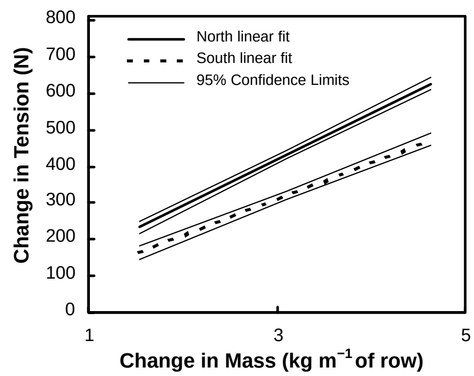

Figure 12. Relationship between accumulated change in known mass and accumulated change in wire tension for data pooled over row and date [ΔT_N = 36.329 + (127.598 × Δkg) (R^2 = 0.87, *n* = 128, d.f. = 1); ΔT_S = 9.531 + (100.491 × Δkg) (R^2 = 0.80, *n* = 131, d.f. = 1)]. The slopes are significantly different in a test for heterogeneity (SS = 76113.85, d.f. = 1, F = 18.89, Pr > F = 0.0001), suggesting that the north end, with its greater initial tension, had more sensitivity to an increase in mass.

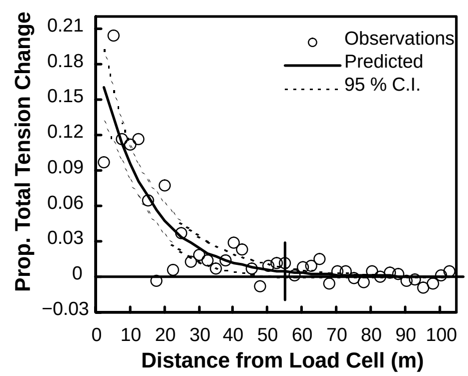

Figure 13. Proportion of the total change in tension as a function of distance from the load cell, modeled as an exponential decay. Vertical bar indicates distance where the lower 95% confidence limit crosses zero.

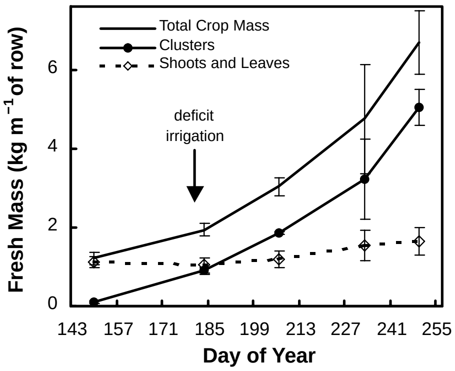

Figure 14. Mean crop mass of vines in the FC treatment rows (±SE, *n* = 3). Deficit irrigation was initiated in July (DOY 182).

Seasonal Pattern of Crop Mass

We deficit−irrigated the vineyard from the beginning of July (DOY 182), about 30 days after fruit set. Destructive sampling showed the success of the irrigation strategy, as vines gained little vegetative mass after that time (fig. 14). Furthermore, for all rows with no fruit, tension in the cordon wire did not increase appreciably between the time of crop thinning and harvest (fig. 8c). On vines of the FC and HC rows, fruit was the primary component of crop mass (kg m^{-1} of row) at harvest, comprising 75% and 61% of the total, respectively. Similar proportions have been observed for above−ground dry matter on potted vines that had been thinned to various yield levels (Edson et al., 1995). The ratio of fruit to vegetative mass varied tremendously through the season in the FC and HC rows because the deficit irrigation approach limited only vegetative growth.

One considerable difficulty in applying a measure of tension in the cordon wire to an estimate of yield lies in accounting for the vine's vegetative mass. In vines that are well−watered, such as the 'Concord' juice grape or the 'Thompson Seedless' table grape, shoots elongate and add leaves during nearly the entire growing season. Thus, while the fruit gains mass so does the vine canopy, both contributing to the tension in the cordon wire. One approach with the load cells may be to collect several years' data on canopy growth to determine whether a given vineyard block is managed well enough to produce consistently sized vine canopies from year to year, and to model that growth according to heat accumulation, or "growing degree days," to normalize for seasonal weather variation. In that case, the canopy's contribution to the total tension in the cordon wire may be considered a constant factor. In deficit−irrigated vineyards, shoot length is controlled by application of water to minimize vegetative growth soon after fruit set. In this situation, vegetative mass changes little during the period of fruit growth, making increases in wire tension easier to interpret. Estimating yield from trellis wire tension may be most readily applicable to deficit−irrigated vineyards and in other trellised crops where vegetative growth naturally slows during the period of fruit development.

Relationship of Increase in Tension to Yield

The mean yield for FC rows was 5.09 kg m^{-1} of row (±0.555 SE) and 3.19 kg m^{-1} of row (±0.423 SE) for HC. This corresponds to low−to−average yields for 'Concord' in Washington (equal to industry average for 2001) and, for the HC rows, low yields. However, the HC row yields were representative of those in premium wine grapes. Yield was presumed to be 0 for the NC treatment. Over the 2001 season, tension increased an average of 899 N (range 625 to 1995 N) on the north row ends and 634 N (range 405 to 1039 N) on the south ends. There was a strong linear relationship between final yield and the change in tension in the cordon wire throughout the season (fig. 15). The slope of this relationship changed during the season because progressively larger changes in tension due to crop growth were regressed against the final yield. At harvest, measured yields were lower than those that would have been predicted by the known mass calibrations (fig. 15D, fig. 16). FC rows were overestimated by an average of 14.5% ±8.1% and HC rows by 10.1% ±4.1%. This is not surprising because vegetation accounted for some of the increase in tension. In addition, there was a difference in spatial scale. Vines nearest the load cell received higher weighting in the tension−based estimate, whereas harvest data represent yield averaged over the entire row. Nonetheless, the yield estimates based on trellis tension and a known mass calibration were well within the industry−wide range of errors inherent in the current method of infrequent hand sampling.

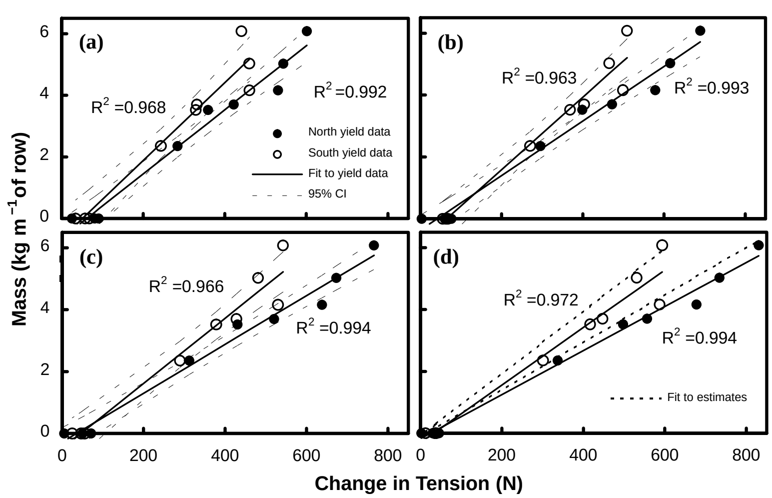

Figure 15. The relationship between tension and yield at four times after manual thinning on DOY 181: (a) pea−sized berries (DOY 187) just after fruit thinning; (b) 60 days post−bloom (DOY 210); (c) veraison, the beginning of berry ripening (DOY 233); and (d) harvest (DOY 260). In (d), the dashed lines indicate expected yield from the relationship of known mass to change in tension since bloom (DOY 148).

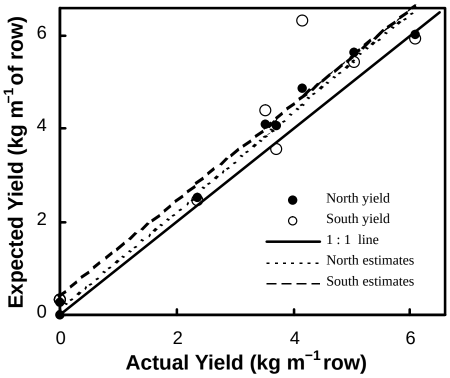

Figure 16. Expected yield estimated from wire tension just prior to harvest and actual yield. Confidence limits (95%) for the north and south relationships overlapped one another and the 1:1 line.

The yield estimates were adjusted by attempting to remove the vegetation's contribution to the increase in wire tension. This led to an underestimation of yield, with the north row ends falling closer to the actual values than the south row ends (data not shown). The vegetation correction was unsatisfactory due to the small numbers of samples that were available for estimates of vegetative mass. One major limitation to field plot research with perennial crops can be the limited number of plants available for destructive sampling. An ideal solution would be the identification or development of a satisfactory non−destructive estimator of vegetative mass, like shoot length, or an optical sensor that could estimate canopy size and mass, so that one could account for the proportion of mass due to vegetation. Until such methods are resolved, non−destructive series of measurements such as shoot length and shoot number could be recorded over several seasons to establish the consistency of the vegetation's contribution to the tension measurement during fruit growth.

CONCLUSION

With further refinements, automated measurements of tension in the horizontal support wire of a trellis should provide an accurate and frequent estimate of fruit mass throughout the season and a method of predicting final yield. A strong relationship was demonstrated between yield and the change in tension from the season's start. By correcting to a standard temperature and using a 48 h moving average, the influence of wire temperature on the tension can be eliminated. The observations also suggest that the measurements are robust against the effects of wind of short duration and low intensity when tension measurements are averaged over several minutes. Additionally, the effects of more intense winds of longer duration can be identified, and the user could compensate for these small effects when applying the tension measurements to yield estimates.

Loading trellis wires with known mass showed that the relationship between an increase in mass and an increase in tension did not vary significantly, nor in any consistent pattern, as the overall tension increased with growth during the season. While there is relative consistency within the system through the season, there were significant differences among vineyard rows in the relationship between change in wire tension and change in known mass. This relationship helps to normalize mass estimates from the rows, thus letting one account for row−to−row variability. Sensitivity, a function of the initial tension, decreased with distance between the load and the load cell. There was a large amount of variability between row ends in the rate of decay for load cell sensitivity and the distance to which a change in mass might be sensed.

The ability to isolate fruit mass from vegetative mass at any moment during the growing season is needed to apply this methodology to the estimation of fruit mass and to yield predictions. An estimate of fruit mass should be simply a matter of reducing the total mass estimate (based on increase in wire tension) by the proportion contributed through vegetative growth. Estimates of yield using the relationship of change in tension to increase in known mass were, as expected, greater than the actual harvested mass, but when the mass contribution from vegetation was removed, yield predictions were reduced below the observed values. An attempt to account for the vegetative component at harvest proved inadequate, largely due to small sample sizes dictated by the size of the experimental vineyard and the perennial nature of the crop.

If growers rely on such vegetative sampling, little advantage will be gained over the current labor−intensive practices. An alternative to sampling might include coupling mass estimates made from trellis wire tensions to fruit−vegetation ratios predicted from growth models. A corollary would be for growers to use or develop historical records relating season−long tension estimates to fruit mass, especially for harvest prediction. This latter possibility would be very similar to the current practice of extrapolating from a few cluster samples during the growing season, but would be vastly improved by the contribution of continuous tension estimates.

For general applicability to growers, future work needs to explore several issues, especially whether the relationships between increasing wire tension and mass (yield) are consistent by season, across vineyards, and among trellis types. If the method is to be used for making early−season predictions of yield, then growth models or non−destructive, inexpensive means are needed to partition the increased mass between fruit and vegetative growth. For a commercial vineyard, one must determine the number of required sensors and their optimal spatial deployment. As the number of sensors per vineyard increases, the cost per sensor and data acquisition system must decrease if the method is to be adopted.

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